Remnants of the Sagittarius Dwarf Spheroidal Galaxy around the young globular cluster Palomar 12

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ABSTRACT

Photometry of a large field around the young globular cluster Palomar 12 has revealed the main-sequence of a low surface-brightness stellar system. This main-sequence is indicative of a stellar population that varies significantly in metallicity and/or age, but in the mean is more metal poor than Pal 12. Under different assumptions for the properties of this population, we find distances from the Sun in the range 17-24 kpc, which encompasses the distance to Pal 12, 19.0 ± 0.9 kpc. The stellar system is also detected in a field 2° North of Pal 12, which indicates it has a minimum diameter of ~ 0.9 kpc. The orbit of Pal 12 (Dinescu et al. 2000), the color-magnitude diagram of the stellar system, their positions on the sky, and their distances suggest that they are debris from the tidal disruption of the Sgr dSph galaxy. We discuss briefly the implications for the evolution of Sgr and the Galactic halo.

Subject headings: Galaxy: formation — Galaxy: structure —Galaxy:halo — (Galaxy:) globular clusters: individual (Pal 12) — galaxies: individual (Sagittarius)

1. Introduction

The picture of building the galactic halo from merging "fragments" resembling dwarf galaxies, which Searle & Zinn (1978, hereafter SZ) proposed on the basis of the properties of the Milky Way globular clusters, is often regarded as the local manifestation of the hierarchical galaxy formation theory whereby dwarf galaxies were the first to form and their subsequent mergers created large galaxies (e.g. Moore et al. 1998; Navarro, Frenk & White 1995). The Milky Way continues to be one of the best places to test this picture, and much of the recent work in this area has focused on the identification of stellar streams left behind in the halo after the accretion of low-mass satellite galaxies (e.g. Yanny et al. 2000; Ibata et al. 2001, Dohm-Palmer et al. 2001; Vivas et al. 2001). The prototypical case of accretion is the present-day tidal destruction of the Sgr dwarf spheroidal (dSph) galaxy, which has deposited at least 4 and probably 5 (Dinescu et al. 2000) globular clusters in the halo and produced a long stellar stream that wraps around the sky. One of the Sgr clusters, the very luminous cluster M54, and the most luminous globular cluster in the Galaxy, ωCen, are suspected to be the nucleus of Sgr (Sarajedini & Layden 1995) and a now extinct dwarf galaxy, respectively (Lee et al. 1999). van den Bergh (2000) has argued that the "young" globulars located in the outer halo might be the nuclei of extinct dSph galaxies and has suggested that searches be made for the vestiges of their parent systems. We report here our survey of a large field surrounding Palomar 12 (Pal 12)

Pal 12 is a remote globular cluster located at a distance of 19 kpc from the Sun. It is among the youngest and most metal rich of the halo globular clusters, which has fueled speculation that has been accreted from another galaxy (e.g., Zinn 1993). On the basis of its age and radial velocity, Lin & Richer (1992) argued that Pal 12 may have been captured from the Magellanic Clouds. The measurement of its proper motion and the determination of its orbit around the Milky Way by Dinescu et al. (2000) have shown that Pal 12 probably

did not originate in the Clouds but in the Sgr dSph galaxy (as suggested first by Irwin 1999). In this paper, we report the detection of a very low density stellar system in the same direction and, to within the errors, the same distance as Pal 12.

2. OBSERVATIONS AND DATA REDUCTION

Pal 12 was observed in B and R Johnson–Cousins filters with the Wide Field Camera (WFC) at the prime focus of the 2.5 m Isaac Newton Telescope (INT) at the Roque de los Muchachos Observatory in June 2001. The WFC holds four 4096 × 2048 pixel EEV CCDs with pixel size $0\farcs33$, which provides a total field of about $35' \times 35'$. The field was centered at $10'$ South of the center of Pal 12 with the purpose of including the extra-tidal regions around the cluster (Field 1). In addition, a field situated 2° North of the cluster's center was also taken with the purpose of gauging the field-star contamination (Field 2). However, this field is not far enough away to avoid the large stellar system that we have discovered in the environs of Pal 12. Another control field at Northern galactic latitute, which was observed during the same run, has been used instead.

Bias and flatfield corrections were made with IRAF. DAOPHOT and ALLSTAR (Stetson 1994) were then used to obtain the instrumental photometry of the stars. For the final photometric list, we selected stars with $\sigma < 0.20$, $-1 < SHARP < 1$ and $0 < CHI < 2$ as provide by ALLSTAR. These criteria reject extended objects, so the background contamination is expected to be only stellar-shaped objects. The atmospheric extinction and the transformations to the standard Johnson–Cousins photometric system were obtained from 52 measurements of 20 standard stars from the Landolt (1992) list. The photometric conditions during the observing run were stable and produced very small zero point errors for the photometric transformation: ± 0.020 mag in B and ± 0.016 in R. The offsets between the different WFC chips were obtained from observations of several standard

fields in each chip, and then removed with a precision of better than 0.01 mag. Taking all uncertainties into account, we estimate the total zero-point errors of the photometry are ~ 0.025 in both filters.

3. THE LOW SURFACE BRIGHTNESS SYSTEM

Figure 1a shows the color-magnitude diagram (CMD) for the WFC field centered on Pal 12 (Field 1). In addition to the main-sequence (MS) of the cluster, a MS-like feature is observed at bluer color, overlapping the MS of the cluster at $B - R \sim 0.8$ and $V > 21.0$. This feature is also clearly seen in the CMD of the field situated $\sim 2°$ North of the center of Pal 12 (Field 2).

This unexpected feature of the Pal 12 diagram is more evident in Figure 1b, which shows the CMD of the extra-tidal field of Pal 12. This includes the part of Field 1 beyond the tidal radius of the cluster (i.e. for $r > 17'$) and one-half of the area of Field 2. These regions have almost indistinguishable CMDs, with the only difference that the density of stars in the MS feature is larger in the cluster's field (Field 1). The CMD of the control field situated at (l,b)=$(28.7, 42.2)$ in the North is shown in Figure 1c. The total area of this field is the same as that plotted in Fig. 1b. The absence of the MS feature in the control field is the most striking difference between these Northern and Southern hemisphere regions. The control field has slightly smaller l and $\mid b \mid$ than the fields in the direction to Pal 12. If the halo is symmetric about the galactic plane and has smooth density contours, either spherical or flattened towards the plane, the control field and not the fields in the direction to Pal 12 should have a higher density of halo stars. This is clearly not the case (compare the regions bordered by $22 >'' V'' > 18$ & $0.6 < B - R < 2.0$ in fig. 1b and 1c).

To check the significance of this detection, we constructed luminosity functions of the

stars in the "V" range 18.0-22.4, where the photometric errors are ≤ 0.05 and ≤ 0.03 for the field near Pal 12 and the control field, respectively. The color range was restricted to $0.6 \leq$B-R≤ 1.1, which should encompass the MS and the subgiant branch of an old stellar system. Its large width ensures that this comparison is insensitive to reddening differences, which are expected to be very small (ΔE(B-V)$\simeq 0$, Schlegel et al. 1998, SFD). Figure 2 shows that for "V"< 20.6 there is little difference between the field near Pal 12 and the control field. Hovever, for $20.8 \leq$"V"≤ 22.4, there is an excess of stars in the field near Pal 12 over the control field, and for every 0.2 mag. bin in this interval, this excess corresponds to several standard deviations.

Figure 2 also compares the luminosity functions with that of a model stellar population, which was constructed from the isochrone calculations of Girardi et al. (2000) for a metal abundance of Z=0.001 ([Fe/H] =-1.3) and an age of 12.6 Gyr. We imposed the same color boundaries as above and transformed to apparent "V" magnitude by adopting the same distance modulus and interstellar extinction as Pal 12. To model the field stars, we fit a quadratic equation to the luminosity function of the stars in the control field. The solid line in Figure 2 is the sum of this function plus the one for the 12.6 Gyr stellar population. It is normalized so that it matches the observed number of stars in the field near Pal 12 for "V"< 19.0. The number of stars in the 12.6 Gyr system was varied until a rough match was obtained between the model function and the observed points for "V"> 21.5. The similarity between this model luminosity function and the observed one over the whole range of "V" suggests that the excess of stars over the control field is caused by a real stellar system at approximately the same distance as Pal 12. Unfortunately, the number of stars is too small to tightly constrain the luminosity function, and firm conclusions about the age or composition of the system cannot be drawn from this match.

To estimate the surface brightness of this system, we used the control field for an

estimate of the field star contamination and produced a decontaminated CMD following the procedure of Gallart, Aparicio & Vílchez (1996). Over the range $20.5 \leq$"V"≤ 22.9 and within the same color range as above, there is an excess of 293 ± 15 MS stars over the background. The comparison of this number with that found in a decontaminated CMD of the main body of the Sgr dSph (Martínez-Delgado et al. 2002) yields an estimate of $\Sigma=$ $30.5\pm$ 0.2 mag arcsec^{-2}. While undoubtedly this system has a very low surface brightness (LSB), we caution that this value is a rough estimate and also note that there is probably a gradient in Σ across the field. This value is the same found by Mateo et al. (1998) in their outermost detection of the Sgr stream, 34° SE from the center of Sgr.

A comparison between Figures 1a and 1b shows that the extra-tidal stellar population is bluer than that of Pal 12 and displays a significant width in color, indicating the presence of a range of age and/or metallicity and/or some depth along the line of sight, as expected of a dwarf galaxy. The simplest explanation is that this MS feature is not due to Pal 12 but to a separate stellar population that is part of a dSph galaxy or a tidal stream from one. The presence of this feature throughout the area covered by Field 2 puts a lower limit of 0.9 kpc on the extension of the system, assuming that it is at the same distance as Pal 12 (19.0 kpc; see below). This size is compatible with the width of a tidal stream crossing the field (e.g. Sgr tidal stream; Newberg et al. 2002) or the projected tidal radius of a typical dSph at the cluster's distance.[1].

While the comparison in Figure 2 between the model and observed luminosity functions illustrates that the LSB system could be at the same distance as Pal 12, it is important to examine this question in more detail. In Figure 1b, the MS appears to terminate at "V"$=20.48 \pm 0.10$. The MS turnoff (i.e., the bluest point of the MS) is probably fainter

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[1] A typical dSph with a tidal radius of $\sim$ 1 kpc would have angular radius of 3 degrees at this distance.

than this (e.g., the turnoff of the 12.6 Gyr population in Fig. 2 occurs at 20.65, $M_V = 4.14$ Girardi et al. 2000), but this point cannot identified with certainty given the small number of stars. It seems unlikely that it could be fainter than "V"=20.9. Adopting this value, a somewhat brighter turnoff luminosity ($M_V = 3.9$), and correcting for the interstellar extinction (E(B-V)=0.037 ± 0.002, SFD), we obtain 23.8 kpc for an upper limit on the distance, if the LSB system is composed of a very old stellar population. For a lower limit under the same assumption, we adopt 20.48 as the turnoff and a fainter turnoff luminosity ($M_V = 4.2$), which yields a distance of 17.1 kpc. It is likely that the LSB population is a mixture of ages and compositions, which is much harder to model. Under the assumption that its stellar population resembles the main body of the Sgr dSph galaxy, we can use the decontaminated CMDs of the LSB system and Sgr (see above) to help set the distance modulus of the LSB system. These CMDs suggest that the MS feature seen in Figure 1b is only the densest part of the MS and that its "termination" at "V"=20.48 corresponds to point in Sgr where $M_V \approx 3.7$ (Layden & Sarajedini 2000). This yields a distance of 21.6 kpc for the LSB system, with an uncertainty of ~ 2 kpc. The distance to Pal 12 is 19.0 ± 0.9 kpc (Rosenberg et al. 1998, but using E(B-V) from SFD), which places it near the middle of the range of estimates for the distance to the LSB system. If they are unrelated, this is a very remarkable coincidence.

Dinescu et al. (2000) have shown on the basis of the orbit of Pal 12 that the Sgr dSph galaxy is likely to be its parent galaxy. Recent surveys of Sgr (Mateo, Olszewski & Morrison 1998; Ibata et al. 2001; Majewski et al. 1999; Yanny et al. 2000; Martínez-Delgado et al. 2001; Martínez-Delgado, Gómez-Flechoso & Aparicio 2002) have shown that this galaxy forms a giant stream that wraps completely around the Milky Way in an almost polar orbit, in good agreement with the predictions of theoretical models (Gómez-Flechoso, Fux & Martinet, 1999; Johnston, Sigurdsson & Hernquist 1999 ; Helmi & White 2001). The position of Pal 12 on the sky ($\sim 40°$ from the Sgr's main body) is very close to that

predicted for the Sgr Southern stream (see Martínez-Delgado et al. 2001). The predicted distance for the Sgr's tidal stream at the cluster's position is $\sim$ 19 kpc (Martínez-Delgado et al. 2002), in good agreement with the distance obtained above for th LSB system.

The CMD of the LSB system also resembles those of previous detections of the Sgr Southern stream. Majewski et al. (1999) reported a MS turnoff at V=21 in a field situated at (l,b)= (11°, -40°), which is $\sim$ 20° from Pal 12. In the Sloan Digitized Sky Survey (SDSS), Newberg et al. (2002) found a similar structure (named S167-54-21.5) in the CMD of a long, narrow region centered on the celestial equatorial and $15° < \alpha < 0°$, that could be also part of the Sgr tidal stream.

As we noted above, the MS of the LSB system is bluer than the MS of Pal 12 and extends to approximately the same bright magnitude. These characteristics suggest that it is more metal poor than Pal 12 ($[Fe/H]$=-1.0; Brown, Wallerstein & Zucker 1997) and may be as old or older than it, since lower metallicity isochrones have brighter turnoffs for a given age. The MS feature has intermediate color between the $[Fe/H]$=-1.7 and -0.7 isochrones of Bertelli et al. (1994), which yields a mean value of ~ -1.2. This is similar to the metallicity of the metal-poor component of the main body of Sgr ($[Fe/H]$= -1.3; Layden & Sarajedini 2000) and the giants in the Northern stream of Sgr (Dohm-Palmer et al. 2001).

4. DISCUSSION

Our detection of a LSB stellar system around Pal 12 strengthens considerably the contention of Dinescu et al. (2000) that Pal 12 originated in the Sgr dSph galaxy. The disruption of Sgr has therefore released at least 5 globular clusters to the Galactic halo (Ibata, Gilmore & Irwin 1994; Irwin 1999), and additional ones may remain undetected

among the globular clusters in the outer halo. Two of the Sgr clusters (M54 and Ter 8) are similar in age to the oldest globular clusters in the Milky Way. A third (Arp 2) is slightly younger than these other two (Buonanno et al. 1998; Layden & Sarajedini 2000). The much younger Sgr cluster (Ter 7) and Pal 12 (Buonanno et al. 1998; Rosenberg et al. 1998) are several Gyrs younger than the other three Sgr clusters, and they are the youngest and most metal-rich globular clusters in the galactic halo. Sgr resembles the Fornax dSph galaxy in having 5 globular clusters, although their histories of cluster formation are significantly different. Only one of the Fornax clusters is clearly younger than the other four, and this cluster (cluster 4, Buonanno et al. 1999) is both older and less metal rich than the youngest Sgr clusters (Ter 7 and Pal 12).

Spectroscopic observations by Brown et al. (1997) have shown that Pal 12 is almost unique among halo globular clusters by having $[\alpha/Fe]$=0.0 instead of ≈ 0.3. This relatively low α abundance is a sign of metal enrichment by Type Ia supernovae (Brown et al. 1997). The measurement of the abundance ratios in several red giants in Sgr by Smecker-Hane & McWilliam (1999) have shown that two metal-poor stars ($[Fe/H] < -1$) are α enhanced while 9 others with $[Fe/H] > -1$ have $[\alpha/Fe] \sim 0.0$. The chemical composition of Pal 12 ($[Fe/H] = -1$, $[\alpha/Fe]$=0.0, Brown et al. 1997) is also consistent with membership in Sgr.

The three "young" Sgr clusters (Arp 2, Ter 7, Pal 12) constitute one quarter of the "young" globular clusters in the Galactic halo (van den Bergh 2000). Many of the other young halo clusters (perhaps all), and at least some of the old clusters may have originated in dwarf galaxies that later merged with the Milky Way. The stellar streams from Sgr show that this process not only added globular clusters to the halo, but also contributed stars of different ages and metallicities, as predicted by the SZ scenario.

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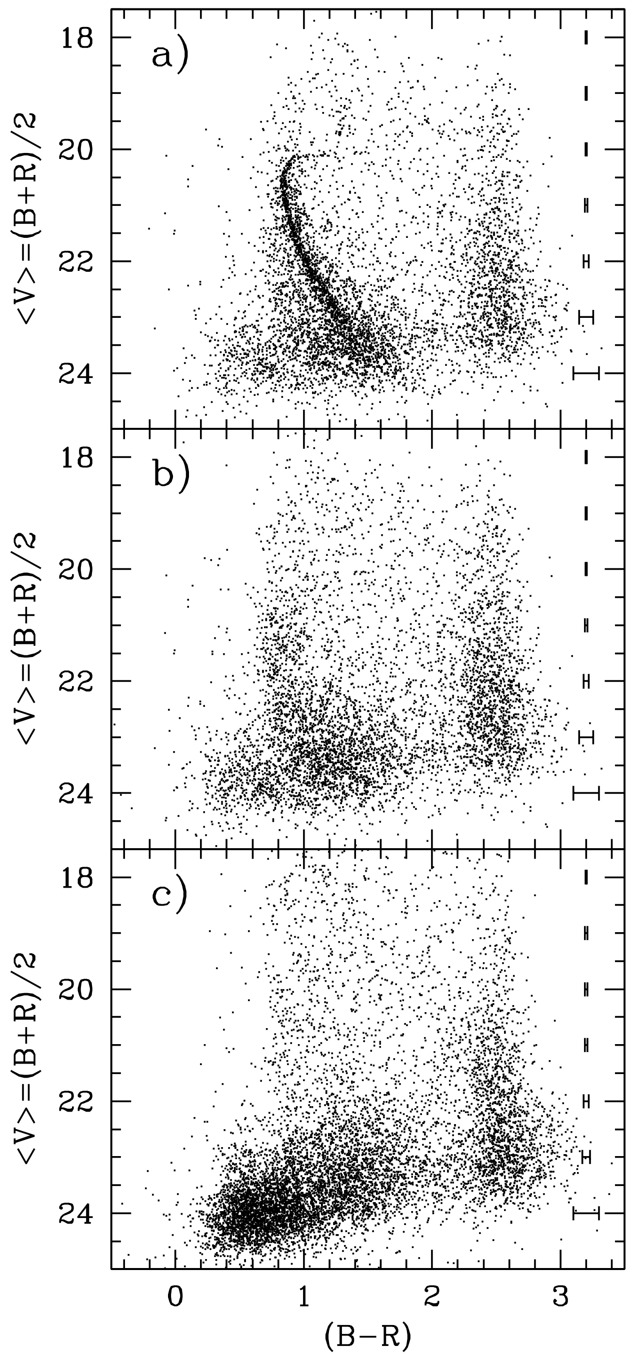
Figure 1. *panel a)* Color-magnitude diagram for the WFC field centered on Pal 12 (Field 1). The narrow main-sequence (MS) of the cluster is clearly delineated. Notice that it is surrounded by a sparser and wider MS-like feature at bluer color; *panel b)* displays the CMD for an extra-tidal field of $35' \times 35'$, half of which is from Field 1 but outside of the cluster's tidal radius ($r > 17'$) and the other half is from Field 2, situated $\sim 2^\circ$ North of Pal 12. The MS feature is most clearly observed at $B - R \sim 0.8$ and $21 < V < 23$; *panel c)* shows the CMD of our control field, which is the same size as the field shown in 1b.

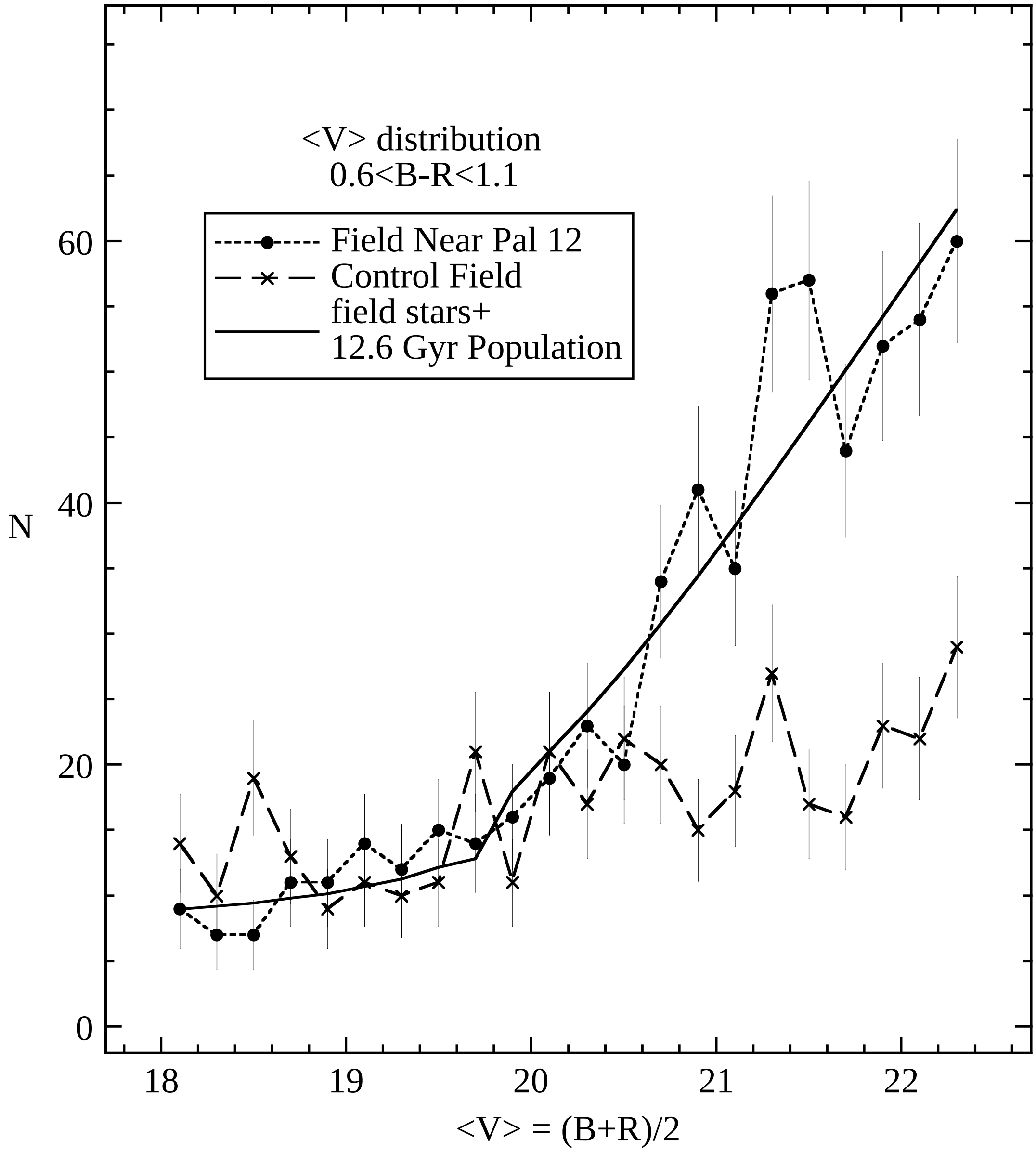
Fig. 2. Comparison of the luminosity functions of the extra-tidal field of Pal 12 and the control field. The solid line is the model LF for a stellar population with age 12.6 Gyr and Z=0.001, adopting the distance and reddening of Pal 12. The error bars are $\pm\sqrt{N}$, where N is the number of stars in each bin.

Table 1. Positions and Integration Times

Field	R.A.(J2000.0)	Dec	l	b	t_B(s)	t_R(s)
Field 1	$21^h46^m38\overset{s}{.}9$	$-21°25'00''$	30.3	-47.7	3600	1800
Field 2	$21^h49^m21\overset{s}{.}7$	$-19°20'10''$	33.5	-47.7	3900	3600
Control	$16^h11^m04\overset{s}{.}0$	$+14°57'29''$	28.7	42.2	9200	9000



a)
b)
c)
<V>=(B+R)/2
(B−R)
18
20
22
24
0
1
2
3


<V> distribution
0.6<B-R<1.1
Field Near Pal 12
Control Field
field stars+
12.6 Gyr Population
N
0
20
40
60
18
19
20
21
22
<V> = (B+R)/2